Momentum anisotropy of the scattering rate in cuprate superconductors

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We examine the momentum and energy dependence of the scattering rate of the high temperature cuprate superconductors using angle resolved photoemission spectroscopy. The scattering rate is of the form $a + b\omega$. The inelastic coefficient b is found to be isotropic. The elastic term, a, however, is found to be highly anisotropic in the pseudogap phase of optimal doped samples, with an anisotropy which correlates with that of the pseudogap. This can be contrasted with heavily overdoped samples, which show an isotropic scattering rate in the normal state.

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There is a general consensus that understanding the normal state excitation spectrum is a prerequisite to solving the high temperature superconductivity problem. Angle resolved photoemission spectroscopy (ARPES) has played an important role in these studies because of the unique momentum and energy resolved information it provides. This includes the observation of dramatic spectral lineshape changes caused by the superconducting transition [1], the large momentum anisotropy of the superconducting gap consistent with d-wave symmetry [2, 3], an anisotropic pseudogap above T_c [4, 5], and the existence of nodal quasiparticles in the superconducting state [6] in contrast to marginal behavior seen above T_c [7, 8]. In this paper, we present data in the pseudogap and normal states of optimal and highly overdoped Bi2212 and Bi2201 compounds, and obtain the energy and momentum dependence of the electron scattering rate. We find that in optimal doped samples above T_c, the scattering rate is of the form $a + b\omega$, with the b term isotropic. The a term, however, is highly anisotropic, with a momentum dependence which follows that of the pseudogap. In contrast, the highly overdoped samples have an isotropic scattering rate. The samples employed for this work are single crystals grown using the floating zone method. The optimal doped $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi2212) samples (T_c=90K) were used in an earlier study [9] as well as the heavily overdoped ($T_c \sim 0$) $Bi_{1.80}Pb_{0.38}Sr_{2.01}CuO_{6-\delta}$ samples [10]. The optimally doped thin film samples of $Bi_2Sr_{1.6}La_{0.4}CuO_y$ were grown using an RF sputtering technique. The samples were mounted with $\Gamma - M$ parallel to the photon polarization [11] and cleaved in situ at pressures less than $2{\cdot}10^{-11}$ Torr. Measurements were carried out at the Synchrotron Radiation Center in Madison Wisconsin, on the U1 undulator beamline supplying 10^{12} photons/sec, using a Scienta SES 200 electron analyzer with a resolution in energy of 16 meV and in momentum of 0.01 $\AA^{-1}$ for a photon energy of 22 eV.

In Figs. 1c and 1d, we plot energy distribution curves (EDCs) along the Fermi surface (Fig. 1a) in the pseudogap state of optimal doped Bi2212 and the normal state of highly overdoped Bi2201. These data reveal that in the optimal doped case, there is a strongly anisotropic pseudogap which is zero in an arc around the node of the d-wave superconducting gap ($\Gamma - Y$ Fermi crossing), and takes its maximal value at the antinode ($M - Y$ Fermi crossing). Moreover, there appears to be a strong anisotropy of the scattering rate, since the spectral peaks

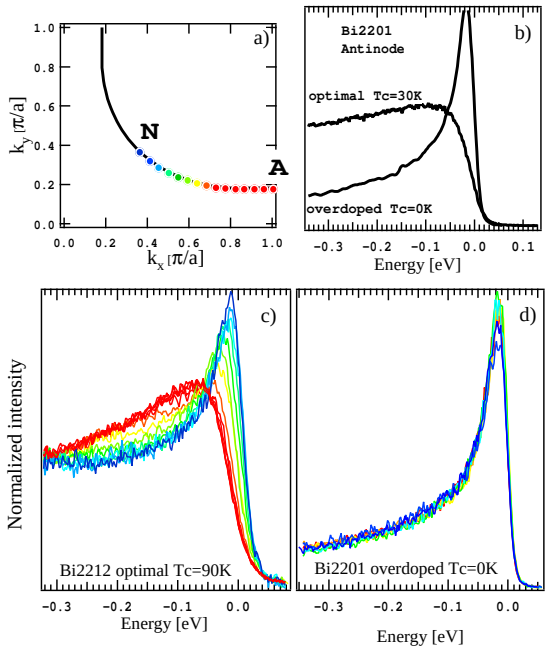

FIG. 1: Energy distribution curves (EDCs) along the Fermi surface: a) points on the Fermi surface where the EDC data were measured (N is the node, A the antinode, of the d-wave gap). b) comparison of the data at the antinode for optimal doped and overdoped Bi2201 obtained at T=50K and T=40K respectively. c) EDC data from optimal doped Bi2212 (T_c=90K) at T=140K. The curves are color coded according to points in panel a). d) same data for overdoped Bi2201 ($T_c \sim 0$) at T=40K.

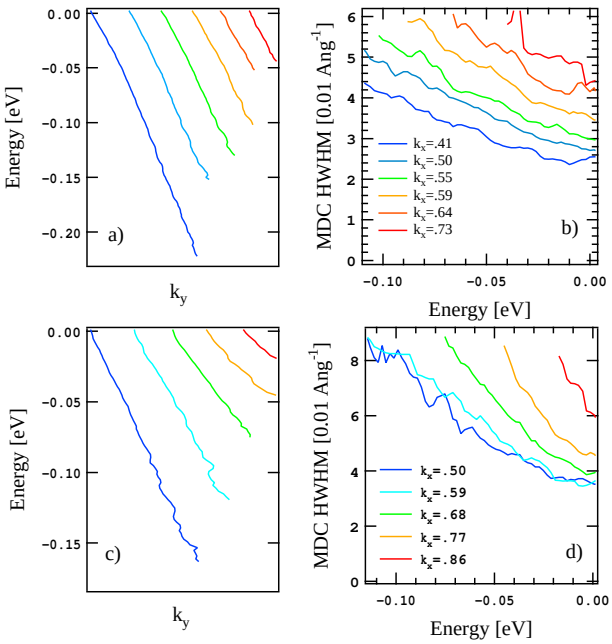

FIG. 2: Dispersion and peak widths obtained from momentum distribution curves (MDCs) for selected momentum cuts parallel to $M-Y$ (labeled by the k_x value along $\Gamma - M$). a), b) Bi2212 at T=140K and c), d) Bi2201 at T=40K.

at the antinode are much broader than at the node. Although this has been suggested to be due to an unresolved energy splitting caused by bilayer mixing [12], a recent study indicates that this is not the case for optimal doped Bi2212 samples [13]. Moreover, in Fig. 1b, we show data at the antinode for optimal doped Bi2201, which has similar spectral characteristics to that of Bi2212, again arguing against a bilayer effect. We can contrast this behavior with that of heavily overdoped Bi2201 in the normal state, where no energy gap is present. In this case, the spectral peak is isotropic around the Fermi surface, indicating that the scattering rate is also isotropic. A similar conclusion was reached in recent studies of heavily overdoped Bi2212 samples where strong bilayer splitting is present [14].

To obtain more quantitative information, we analyze momentum distribution curves (MDCs) [8]. As we pointed out earlier [9], the MDC halfwidth (in the absence of an energy gap) is equal to the imaginary part of the self-energy at that energy, $Im\Sigma(\omega)$, divided by the bare Fermi velocity, v_{F0} (not the renormalized one, v_F). In Fig. 2, we plot the dispersion and peak widths obtained from MDCs along selected cuts in momentum space parallel to the $M-Y$ direction. The first interesting point to note is that the Fermi velocity (slope of the MDC dispersion) appears to be fairly isotropic in optimal doped Bi2212, a conclusion reached in an earlier ARPES study as well [15]. This is further quantified in Fig. 3d, where the velocity at the Fermi energy is plotted around the Fermi surface. This can be contrasted to heavily overdoped Bi2201 (Figs. 2c and 3e), where the Fermi velocity is highly anisotropic. The latter result is consistent with a previous tight binding fit to normal state ARPES dispersions in overdoped Bi2212 [16]. Moreover, the velocity in optimal doped Bi2212 appears to increase slightly as the antinode is approached, in contrast to the slight decrease observed by Valla *et al.*[15]. This difference occurs for two reasons. First, the momentum cuts are parallel to $M-Y$. Though these cuts are normal to the Fermi surface near the antinode, a cut through the node is rotated 45 degrees from the normal. As a consequence, the Fermi velocity in the region near the node is underestimated by up to a factor of $\sqrt{2}$. Second, the appearance of a pseudogap in the spectrum will artificially inflate the value of the Fermi velocity determined from MDCs for energies within the pseudogap [17], since the effect of the gap will cause the dispersion to become more vertical. Thus, the velocity is being overestimated in the region near the antinode. Therefore, we conclude that the true Fermi velocity is roughly isotropic, with a small decrease as the antinode is approached. The strong anisotropy observed in the Bi2201 case is due to the closeness of the saddlepoint of the dispersion at M (where the velocity

is zero) to the Fermi energy for this heavily overdoped sample [10]. Stated another way, the small anisotropy in the optimal doped case implies that the saddlepoint at M is significantly far from the Fermi energy.

The energy dependence of the MDC peak widths for the various momentum cuts is shown in Figs. 2b and 2d. To a good approximation, the result for a particular cut can be fit to the form $a + b\omega$. This is analogous to the $a + bT$ form indicated for the temperature dependence of MDC widths previously reported by Valla *et al.*[15]. In Fig. 3b, we show the momentum dependence of the a and b terms extracted from the MDC HWHM in Fig. 2b. To complement these results, we have also fit EDCs along the Fermi surface using a model self-energy, Σ. We have tested both quadratic and linear energy dependences for $Im\Sigma$ and found that only the latter is an adequate description of the data. $Re\Sigma$ is determined by Kramers-Kronig transformation of $Im\Sigma = a + b\omega$, assuming the latter saturates at a constant value beyond a cutoff energy of 0.5 eV. In Fig. 3c, we show the values of the a and b coefficients obtained from these EDC fits [18].

We first note that the b term is isotropic in both plots. Since the MDC HWHM is equal to $Im\Sigma/v_{F0}$, this implies that the bare velocity (v_{F0}) is also isotropic. The isotropy of b provides strong support of the original marginal Fermi liquid conjecture [19]. At first sight, it would appear that the Bi2201 case is different, since the slope of the curves in Fig. 2d appears to increase as the antinode is approached. But once the velocity is divided out (Fig. 3d) [20], we find in this case as well that the b term for $Im\Sigma$ is isotropic, which is consistent with the isotropy of the EDC lineshapes shown in Fig. 1. We note that the b term is less well defined in the Bi2201 case due to curvature observed in Fig. 2d. This is expected, since as the hole doping increases, the lineshapes become more Fermi liquid like, and thus one expects a crossover from linear to quadatic behavior in ω.

The a term in optimal doped Bi2212 (zero intercept in Fig. 2b) is found to be highly anisotropic (Figs. 3b and 3c), as noted in the earlier study of Valla *et al.*[15]. This is consistent with the strong anisotropy of the EDC lineshapes shown in Fig. 1c. Anisotropy in the "zero intercept" is also evident in the heavily overdoped Bi2201 sample (Fig. 2d), but in this case, it can be accounted for by the anisotropy of the Fermi velocity, thus the a term in $Im\Sigma$ in this case is isotropic (again, this is consistent with the isotropy of the EDC lineshapes shown in Fig. 1d). The anisotropy of the a term in the optimal doped sample has been attributed to off planar impurities [21]. On the other hand, we note the remarkable similarity between the anisotropy of this term (Fig. 3b) and that of the pseudogap (Fig. 3a). This indicates to us that the anisotropy is probably not due to impurity scattering, but rather a consequence of the pseudogap. This would be consistent with the observation of isotropic lineshapes for more heavily overdoped samples of Bi2212 [14], where

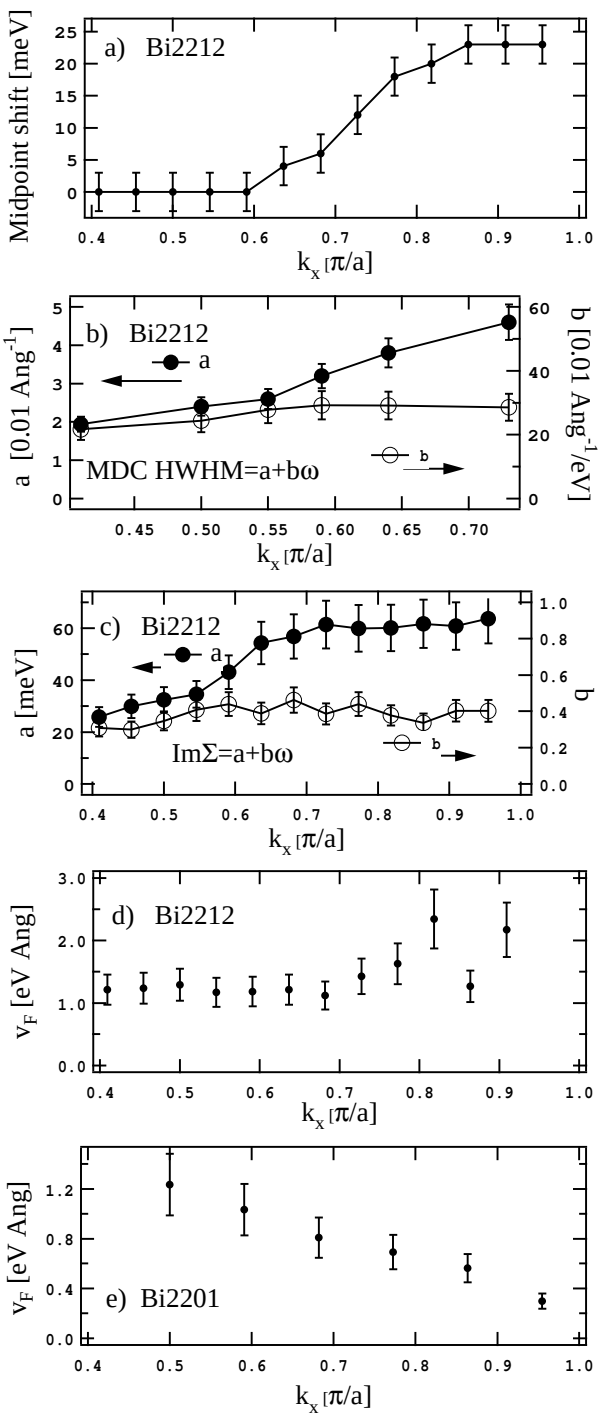

FIG. 3: a) Position of the midpoint of the leading edge of the EDC around the Fermi surface for Bi2212 obtained from Fig. 1c (k_x labels the momentum cut as in Fig. 2, with $k_x = 0.4$ corresponding to the node and $k_x = 1.0$ to the antinode). This is an approximate measure of the pseudogap. b) momentum dependence of the "a" (constant) and "b" (linear in ω) terms of MDC HWHM obtained by fitting data from Fig. 2b. c) momentum dependence of the "a" (constant) and "b" (linear in ω) terms of $Im\Sigma$ obtained by fitting EDCs from Fig. 1c. d) momentum dependence of the Fermi velocity (slope of the dispersion in Fig. 2a). e) the same as d), but for overdoped Bi2201 (Fig. 2c).

no pseudogap is present.

One possibility for explaining this intriguing observation is to consider MDCs in the presence of a spectral gap [17]. At the Fermi energy ($\omega = 0$), the resulting MDC HWHM is equal to $\sqrt{\Gamma^2 + \Delta^2}/v_{F0}$, where Γ is the lifetime broadening and Δ the energy gap. In the limit of small Γ, the anisotropy of the MDC HWHM follows that of Δ [22]. Thus, in this picture, we would interpret "a" as containing a background contribution due to instrumental resolution and weak impurity scattering, and an anisotropic term due to the pseudogap. But other possibilities could also be considered, such as the cold spots model of Ioffe and Millis, where a highly anisotropic scattering rate is conjectured due to scattering from d-wave pairing fluctuations [23, 24].

In conclusion, we find that the normal state scattering rate in the cuprates can be approximated by the form $a + b\omega$. The inelastic b term is found to be isotropic, which is a necessary ingredient in the marginal Fermi liquid conjecture [19]. In contrast, the a term is found to be anisotropic for optimal doped samples, with the anisotropy linked to that of the pseudogap. For energies within the pseudogap, this term can be attributed to the influence of the gap on broadening the MDC linewidths, and thus should not be included in the "normal" self-energy when analyzing transport data, a conclusion also reached by Millis and Drew [25].

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